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Self-switching diodes as RF rectifiers: evaluation methods and current progress

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ABSTRACT

In the advancement of the Internet of Things (IoT) applications, widespread uses and applications of devices require higher frequency connectivity to be explored and exploited. Furthermore, the size, weight, power and cost demands for the IoT ecosystems also creates a new paradigm for the hardware where improved power efficiency and efficient wireless transmission needed to be investigated and made feasible. As such, functional microwave detectors to detect and rectify the signals transmitted in higher frequency regions are crucial. This paper reviewed the practicability of self switching diodes as Radio Frequency (RF) rectifiers. The existing methods used in the evaluation of the rectification performance and cut-off frequency are reviewed, and current achievements are then concluded. The works reviewed in this paper highlights the functionality of SSD as a RF rectifier with design simplicity, which may offer cheaper alternatives in current high frequency rectifying devices for application in low-power devices.

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1. INTRODUCTION

Advances in the innovation and development of the semiconductor industry following the Moore's law classical scaling [1] had allowed the industry to double the processing power every 18 months until the last decade, where it is impossible to continually increase both frequency and doubled the transistor number in a chip because of the fundamental thermal limit in the ICs. This has started the second More than Moore's era with equivalent scaling [2]. The approaches of this era which introduced the usage of strained silicon, high-κ/metal gate, FinFET, and other semiconductor material (e.g. Germanium) had increased the performance of transistors and the non-digital functionalities e.g. radio frequency (RF) communication, power control and passive components [3] which bring us to the onset of the internet technologies era by the theme of Internet of Things (IoT). The focus of the semiconductor industry in this era has changed to the third phase of scaling, the three dimensional (3D) power scaling where the focus has been changed from shrinking individual chips to emphasizing capability integration and power consumption reductions [4, 5] which aim for mobile, high connectivity and low power consumption devices. This scaling is in-line with the roadmap of IoT which aims for miniaturization, power-efficient electronics, and available spectrum in the year 2020 [6]. The size, weight, power and cost (SWaP-C) demands for the IoT ecosystems also creates a new paradigm for the hardware where smart power management, improved power efficiency, wireless power transmission and energy harvesting needed to be investigated and made feasible for IoT applications [7].One of the solutions for mobile, rechargeable device is by wireless power transfer (WPT) by harvesting ambient energy from surroundings in micro or nano-scale power source [8]. The harvester in general, heavily depends on the diode, which enables switching-type conversion e.g. direct current to direct current (DC–DC) or alternating current to direct current (AC–DC) conversion [9]. These diodes have been used in various harvesters as rectifier where it reacts differently depending on the sign of the voltage across it. The capability of the rectifying diodes to be used in this microwave region need to be carefully examined to ensure that the electron transport in the device can cope with the high transition rate between the positive and the negative cycles.

The uses of conventional pn junction diodes as rectifier are irrelevant for this high frequency application because of the phase lag caused by the slower transition of minority carriers [10]. Hence, unipolar or majority carrier devices such as tunnel diodes, back diodes, and Schottky diodes are utilized in high frequency region. However, because of greater susceptibility to RF burnout, circuit complications, and fabrication difficulties, tunnel and back diodes have not found as wide acceptance as mixers and detectors at microwave frequencies [11]. Most widely used and marketed rectifier in the microwave region is the Schottky diode which is formed by depositing a whisker-like metal on a semiconductor. This semiconductor-metal junction creates a barrier (known as Schottky barrier) between both materials which results in rectifying behavior [12]. Rectification using Schottky devices may reach high frequencies but it has limitations in term of sophisticated nano-gates fabrication process which often results in parasitic effects [13, 14]. Furthermore, the coupling of a Schottky device with antennas and waveguide as well as the fabrication of large arrays also pose additional engineering issues [15].

A less explored device with promising capability for zero-bias high frequency detection, the self-switching diode (SSD) has recently introduced by Song et al. [16]. The SSD is one type of planar unipolar device, which is more adequate in term of fabrication complexity compared to the most used Schottky diode where it does not involves junctions, doping, and third gate terminal [17]. The planar structure of the SSD can reduced the intrinsic device's parasitic capacitance for high-frequency operations [18]. The fabrication simplicity and rectification capability of SSD make it a suitable candidate for a low cost high-frequency detectors.

This paper provides insights into the works related to the rectification performance parameters of SSD and its cut-off frequency fc detection. First, we provide an explanation on the rectification principle in a general square law diode detector to have a better view on the parameters affecting the rectification performance in non-linear devices. Then, we introduced the typical structure of an SSD and its operational principle to understand the general behavior of electron and current in the structure. Then, we reviewed published works that related to the evaluation and improvements of the rectification performance and fc of the SSD. Finally, we concluded the performance and suitability of a SSD as a RF rectifier.

2. NONLINEAR ANALYSIS OF DETECTOR DIODES

An ideal current-voltage (I-V) characteristic of a square-law detector diode has a nonlinear *I-V* characteristics, and can be analyzed using a nonlinear device analysis, where *I* is the function of *V*:

$$I = f(V) \tag{1}$$

The total inputs of the diodes can be from the RF signal and DC bias where *V* across the diode are the addition of applied DC bias voltage V_o and RF input of $v_{RF}=A\cos(\omega t)$, where *A* is the amplitude of the input RF signal:

$$V = V_o + v_{RF} \tag{2}$$

Expanding (2) using Taylor Series [19-20] with evaluation at *Vo (a=Vo)*, function *f (V)* becomes:

$$f(V) = \sum_{n=0}^{\infty} \frac{f^{(n)}(V_o)}{n!}(V - V_o)^n = \sum_{n=0}^{\infty} \frac{f^{(n)}(V_o)}{n!} v_{RF}{}^n \tag{3}$$

Substituting (3) in (1) resulted in the total *I* of

$$I = I_o + \frac{v_{RF}}{1!} f^{(1)} + \frac{v_{RF}{}^2}{2!} f^{(2)} + .. + \frac{v_{RF}{}^n}{n!} f^{(n)} \tag{4}$$

where I_o=function of V_o [$I_o=f(V_o)$] and $f(n)$=nth order derivatives of the function V_o. Substituting $v_{RF}=Acos$ (ωt) in (4) yields;

$$I = I_o + \frac{Acos(\omega t)}{1!} f^{(1)} + \frac{[Acos(\omega t)]^2}{2!} f^{(2)} + \ldots + \frac{[Acos(\omega t)]^n}{n!} f^{(n)} \tag{5}$$

By using power reduction formulas derived from the double-angle and half-angle formulas [21], (5) can be rewrite as:

$$I = I_o + \underbrace{\left[\frac{A^2}{4} f^{(2)} + \frac{A^4}{64} f^{(4)} + .. \right]}_{A} + \underbrace{\left[Af^{(1)} + \frac{A^3}{8} f^{(3)} + .. \right]}_{B} \cos(\omega t) + \ldots \tag{6}$$

where bracket A refers to the rectified current Δi, and the later bracket, B in (6) attributed by the RF related current. Only the first term of Δi is significant in small-signal approximation, thus the rectified DC voltage Δv is equal to

$$\Delta v = R_D \Delta i = \frac{\Delta i}{f^{(1)}} = \frac{A^2 f^{(2)}}{4 f^{(1)}} \tag{7}$$

where: $R_D=1/f^{(1)}$=differential resistance of the diode
A=the amplified input signal
$f^{(1)}$=derivatives of the I-V function (1st order)
$f^{(2)}$=derivatives of the I-V function (2nd order)
$f^{(2)}$ is also known as the bowing coefficient in the I-V function [22, 23].

The rectification performance of nonlinear devices can then be calculated using the curvature coefficient γ, defined as the ratio of $f^{(2)}$ to $f^{(1)}$

$$\gamma = \frac{f^{(2)}}{f^{(1)}} \tag{8}$$

which relates to Δv in (7). The rectifying capabilities can also be quantified using the current responsivity β which indicates the conversion capability to rectify current. In a square law regime where rectified current varies linearly to the RF power, β is constant and equal to the quadratic responsivity β_0 [24] which can be predicted from the I-V characteristics where

$$\beta = \beta_0 = \frac{1}{2}\gamma \tag{9}$$

For an effective rectification performance at zero-bias, β_0 above 3.5 V^{-1} is desired [25, 26].

3. OPERATIONAL PRINCIPLE OF SSD

A typical structure of a SSD is shown in Figure 1(a). The asymmetrical structure between two electrodes can be realized with a simple lithography process. The nonlinear behavior of the device can be obtained by controlling the electric field independent zone (depletion region) of the asymmetric channel between two electrodes as shown in Figure 1(b). The channel is largely depleted when no voltage is applied across it because of the surface states at the etched boundaries. At positive bias, the depletion region inside the channel decreases allowing more electrons to pass across the channel see Figure 1(c). And in negative bias, the depletion zone inside the channel increases, hence completely pinching-off the channel preventing the flow of electrons through the channel as shown in Figure 1(d). This electrical behavior will result in a nonlinear I-V characteristic, where it is similar to a conventional p-n diode but in the absent of any doping junction and barrier structure.

4. ELECTRICAL CHARACTERIZATION OF SSD AND RECTIFICATION PERFORMANCE EVALUATION

Owing to the switching principle of SSD, which is based on the depletion region formed in the asymmetrical channel, the thickness and shape of the depletion region in the channel can be varied to alter the electrical characteristics of the device. Due to that, many research works were conducted on the characterization of SSD using various structural parameters see Figure 2 in various materials and structures to control the *I-V* characteristics of the device.

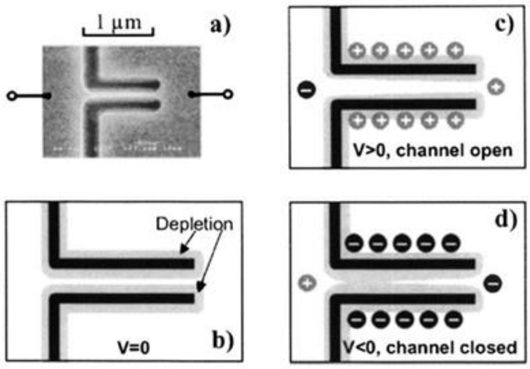


Figure 1. (a) Scanning electron micrograph of a typical SSD, (b) shows the depletion region formed close to the etched boundaries. Depending on the sign of the applied voltage the effective channel width will increase, (c) or reduce, (d) Giving rise to the diode-like characteristics [16]

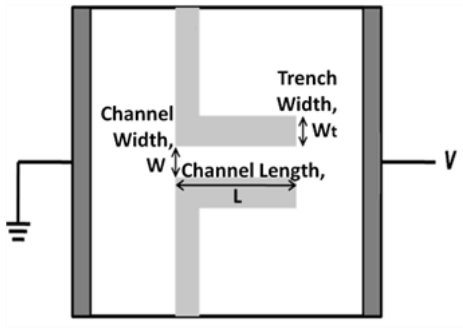


Figure 2. The structural parameters involved in characterization of SSD

Among them are the variations of the channel width W [16], [27−31], channel length L [16], [28−32], trench width Wt [29−35], temperature T [16], [27], [29], [33], [36], [37], and dielectric permittivity εr [34, 36-38]. In addition, the usage of smallest possible Wt of 5 nm [28] was proposed for future technology design. Furthermore, studies on the shape of the dielectric channel were also reported and concluded [38, 39]. These evaluations on particular structural parameter had assisted in term of understanding the behaviour of the depletion region and improvement of the I-V characteristics (e.g. forward current Ifwd, threshold voltage Vth, and leakage current Ileak) in SSD as exampled in Table 1 for InGaAs based SSD [29] (Note that, these behaviours might be varied in different substrate and structure). Thus, the understandings of the electrical behaviours of the SSD are crucial because it highly contributes to the γ which shows the rectification performance of non-linear device as explained in Section 2.

Table 1. Electrical behaviour of InGaAs SSD in various structural parameter variations

Increased Parameters	Treshold Voltage V_{th}	Forward Current I_{fwd}	Leakage Current I_{leak}
Channel Length L	Increase	Decrease	Decrease
Trench Width W_t	Increase	Decrease	-
Channel Width W	Decrease	Increase	Increase
Dielectric Permittivity ε_r	Decrease	Increase	-
Temperature T	Decrease	Increase	Increase

With the knowledge of the relations in the structural parameters to the electrical behaviors, the peak of γ can be predicted and the *I-V* characteristics of the device can be controlled by variation of these structural parameters to obtain efficient zero-bias rectification performance [29]. The rectification performance of SSD can be evaluated in term of β obtained from the γ of the device. However, in some published works, the evaluation of the rectification performance is represented by voltage sensitivity (instead of current responsivity β) which is represented by the value of γ/4 [40].

5. EVALUATION OF CUT-OFF FREQUENCY

Device modelling of SSD has been introduced by using MOSFET square law as the basis, with model assumptions of total capacitance *C* and series resistance R_S values in SSD [41]. This has enabled the theoretical calculation of f_c, direct from the structural parameters and *I-V* characteristics using the general equation of

$$f_c=1/(2\pi R_s C) \ [29, 41].$$

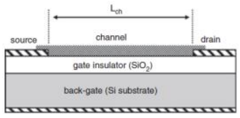
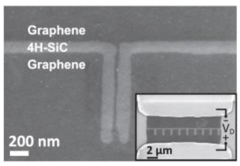
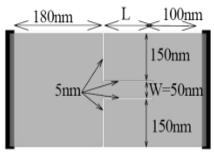
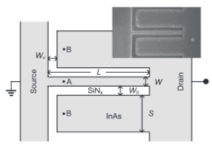
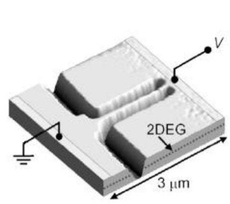
The f_c evaluation by means of simulation can also be conducted by using AC transient analysis in device simulators where the AC signals are assigned to imitate the RF waves absorbed by the diodes [28-29, 38]. The resulted mean current from the AC transient analysis can then be calculated to determine f_c.

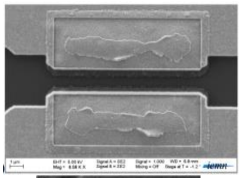
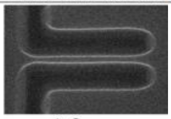
The f_c evaluation using experimental works using RF network analyzer with an array of SSDs connected to rectenna were conducted using 18 parallel SSDs [40], using 43 SSDs [42], and by using 2000 SSDs in array configuration, by coupling to a bow-tie rectenna [23] and a spiral antenna [43]. Proper choose of the SSDs in array configurations can reduced the value of R_s and can improve the impedance matching between the antennas and the device.

6. SSD USING VARIOUS MATERIALS

Apart from the structural characterization, researches on SSD using various materials were done in attempts to increase β and f_c of the device as shown in Table 2. The voltage sensitivity of the device is represented by the value of $\gamma/4$ (refer Section 4) [40], and the Noise Equivalent Power (NEP) is defined as the noise power density over the detection sensitivity [23] where it is represented by the minimum detectable power per square root bandwidth ($W/Hz^{1/2}$) [44]. Researches using various materials were conducted not only by employing semiconductor materials, but also by using other green materials [45] such as P3HT [46] and MOS_2 [47], but there are no records on the mobility and f_c. However, SSD fabricated on graphene possess a large number of carrier density, but having a low mobility value, up to 1400 cm^2/Vs with largest recorded detection at 67 GHz, as shown in Table 2.

Table 2. Self-switching devices using various materials and their electrical performances

Institution	Material	Carrier Density, Mobility	Voltage Sensitivity	Noise Equivalent Power (NEP)	Cut-off Frequency f_c	Representative Image	Ref.
Fujitsu Lab., Japan	ZnO	NA, 0.35 cm^2/Vs	NA	NA	50 Hz		[32]
Chalmers Univ. of Tech., Sweden & Linköping Univ., Sweden	hydrogen-intercalated epitaxial graphene on SiC	NA , ~1400 cm^2/Vs	NA (γ=0.35 V^{-1})	~ 2.2 $nW/Hz^{1/2}$	67 GHz at zero-bias		[48]
Univ. of Salamanca, Spain	InAlAs/ InGaAs	0.3×10^{12} cm^{-2}, NA	NA	NA	2 THz		[28]
Univ. of Lille, France	InAs/AlGaSb	1.5 x 10^{12} cm^{-2}, 26000 cm^2/Vs	NA NA	65 $pW/Hz^{1/2}$ NA	50 GHz 600 GHz		[42]
Univ. of Manchester , U.K	GaAs/ AlGaAs	5.95 x 10^{11} cm^{-2}, ~7000 cm^2/Vs (T=300K) 5.55 x 10^{11} cm^{-2}, ~72000 cm^2/Vs (T=77 K)	150 mV/mW (Sensitivity at zero-bias) 300 mV/mW (sensitivity at 10 nA bias)	330 $pW/Hz^{1/2}$	1.5 THz		[23]
Inst. of	GaN/AlG	1.1 x 10^{13} cm^{-2},	NA	NA	320 GHz		[49]

Institution	Material	Carrier Density, Mobility	Voltage Sensitivity	Noise Equivalent Power (NEP)	Cut-off Frequency f_c	Representative Image	Ref.
Electronics, Microelectronics &Nanotech., France	aN	1800 cm^2/Vs					
Univ. of Manchester, U.K	InP/InGaAs/InP	1.0 x 10^{16} m^{-2}, 450000 cm^2/Vs (T=4.2 K)	75 mV/mW	NA	110 GHz		[40]

The mobility of SSD fabricated using ZnO, ITO, and SOI are very low with mobility of 0.35, 14.5, and 400 cm^2/Vs, respectively, and with only f_c of 50 Hz recorded in ZnO. In contrast, SSD fabricated on III-V materials such as InGaAs, AlGaAs, AlGaSb, and AlGaN have remarkably high mobility with the highest observed in InGaAs/InP with value of 450000 cm^2/Vs. The highest detection frequency of SSD has been recorded using InGaAs at 2 THz by simulation. Nevertheless, by experimental works, the highest detection frequency of 1.5 THz has been observed in AlGaAs. With prudent considerations on the device material, the mobility of the device may be improved and contributes to higher f_c.

7. RECTIFICATION AND CUT-OFF FREQUENCY PERFORMANCE

As to our knowledge, the highest β value of 15 V^{-1} was achieved using InGaAs/InAlAs based SSD with parameter of W=70 nm, L=0.8 μm, and W_t=50 nm with γ peaks at zero-bias [29]. This value indicates high efficiency of the energy conversion in the rectification process (minimal β of 3.5 V^{-1} are required for efficient conversion process). f_c value of ~80 GHz has been achieved using the same structure using Silvaco ATLAS simulator. Highest f_c value of 1.5 THz was achieved by experimental works using GaAs/AlGaAs substrate, with 150 mV/mW sensitivity at zero-bias [23], showing the capability of SSD to works up to the THz region. By Monte Carlo simulation, f_c of 2 THz has been achieved using InGaAs/InAlAs substrate with parameters of W=50 nm, L=100 nm, and W_t=5 nm. However, the etching process of 5 nm channel might be a big hurdle in nowadays practical application.

8. CONCLUSION

Since SSD was first introduced in 2003, many research works were conducted to improve the rectification performance and cut-off frequency of the device. With prudent considerations on the structural parameters and materials, it is proven that the SSDs are capable to efficiently work as rectifiers at high frequency region. The simplicity of the design and process used in these devices may offer cheaper alternatives in current high frequency rectifying devices for application in low-power devices.

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